Final Report on

Testing, Generating, and Explaining Control Procedures

for Reactive Hybrid Systems: The MARS Project

NASA Grant NAG 2-887

Stanford University Knowledge Systems Laboratory
in collaboration with
Xerox Palo Alto Research Center

Richard Fikes
Principal Investigator, Stanford KSL

Yumi Iwasaki
Associate Investigator, Stanford KSL

Daniel G. Bobrow
Vijay Saraswat
Principal Investigators, Xerox PARC

Submitted to
NASA-Ames Research Center

October 15, 1996

OCT 1 8 1996
CA.SI

Knowledge Systems Laboratory
Department of Computer Science
Stanford University

Final Report on

Testing, Generating, and Explaining Control Procedures

for Reactive Hybrid Systems: The MARS Project

Project Summary

The economics and power of digital computation make it the medium of choice for integrating and controlling complex systems of electro-mechanical and computational components. However, the modeling, testing, and analysis of these systems and of procedures for controlling them has become a difficult task; particularly when the system is best described using a mix of discrete and continuous models, and their control involves maintaining real-time constraints. Such systems are called *reactive hybrid systems* and include major subsystems of NASA's space shuttle and space station and of Xerox's document processing products. In this project, Stanford University's Knowledge Systems Laboratory and the Xerox Corporation's Palo Alto Research Center have investigated fundamental theoretical issues in the semantics of hybrid systems that must be addressed in order to solve these problems.

Accomplishments

The focus of the project was on developing a well-founded semantics for the language used to describe hybrid reactive systems. The key technical problem was to identify a semantics that accommodates a sequence of discrete instantaneous actions or changes while continuous activity simultaneously takes place. Discrete event formalisms clearly do not accommodate continuous change, whereas most other formalisms do not accommodate discrete change. While work on hybrid temporal logics is closely related, it has been descriptive, rather than prescriptive and computational in nature. Because our long-term goals include the generation, composition, and validation of control procedures, it was essential that the methods we developed were effectively computable. Following are accomplishments in specific areas.

Semantics of hybrid systems

- We developed two, possibly formally equivalent, semantics for hybrid system descriptions. The first is based on real analysis with limits, the second is based on non-standard analysis. The semantics based on a non-standard model of time was reported in [Iwasaki, Farquhar et al. 1995].

Representation of hybrid systems

- We augmented the Compositional Modeling Language (CML) [Bobrow, Falkenhainer et al. 1996] with constructs for specifying discrete changes.

- We implemented a basic timed concurrent constraint language, TCC [Saraswat, Jagadeesan et al. 1994; Saraswat, Jagadeesan et al. 1994; Saraswat, Jagadeesan et al. 1995] interpreter and developed algorithms for compiling TCC programs into finite state machines.

- We extended TCC's semantics to handle continuous change.

- We augmented the causal functional representation language, CFRL [Iwasaki, Fikes et al. 1993; Iwasaki, Vescovi et al. 1995], to allow control procedures involving discrete actions and time-outs to be described. The augmentation was reported in [Iwasaki, Engelmore et al. 1994]. This will support the validation of control procedures against a model of the system being controlled.

Model construction
- We built models of example systems to highlight the difficulties that arise when modeling hybrid systems.
- We translated aspects of the Reaction Control System from CML into TCC.
- We developed discrete paper path models in TCC.
- We developed a detailed formal model of the paper path behavior. The model was reported in [Gupta and Struss 1995].
- We developed a hybrid paper path model in CML, augmented with language constructs for representing discrete control actions that reflect the semantics of a hybrid system based on a non-standard model of time.

Simulation
- We augmented the model construction and reconfiguration facility of the Device Modeling Environment (DME) [Low and Iwasaki 1993], a model formulation and simulation system developed at KSL, to handle models in CML extended with constructs for discrete changes.
- We simulated the hybrid paper path model with DME.

In summary, this project produced results in the semantic and representational issues of hybrid systems. We believe that those results will provide a firm theoretical ground for further development aimed towards important practical goals including
- Interactively composing structural and behavioral models of reactive hybrid systems from models of individual components,
- Simulating such systems and their control procedures,
- Testing whether such systems and their control procedures satisfy functional specifications,
- Explaining simulation and testing results, and
- Generating control procedures and command sequences for such systems that produce desired system behavior without violating operating constraints of system component

Publications

Gupta, V. and Struss, P. (1995). *Modeling a copier paper path: a case study in modeling transportation processes.* The Ninth International Workshop on Qualitative Reasoning, Amsterdam,

Iwasaki, Y., Engelmore, R., Fehr, G., Fikes, R., Farquhar, A., et al. (1994). *Operator Procedure Verification iwth a Rapidly Reconfigurable Simulator.* The Third International Symposium on Artificial Intelligence, Robotics, and Automation for Space,

Iwasaki, Y., Farquhar, A., Saraswat, V., Bobrow, D. and Gupta, V. (1995). *Modeling time in hybrid systems: How fast is "instantaneous"?* Fourteenth International Joint Conference on Artificial Intelligence, Montreal,

Iwasaki, Y., Vescovi, M., Fikes, R. and Chandrasekaran, B. (1995). Causal Functional Representation Language with Behavior-Based Semantics. *Applied Artificial Intelligence* **9**(1): 5-31.

Saraswat, V., Jagadeesan, R. and Gupta, V. (1994). *Foundations of Timed Concurrent Constraint Programming.* IEEE Symposium on Logic in Computer Science,

Saraswat, V., Jagadeesan, R. and Gupta, V. (1994). Programming in Timed Concurrent Constraint Programming. *Constraint Programming.* Springer Verlag.

Saraswat, V., Jagadeesan, R. and Gupta, V. (1995). *Default Timed Concurrent Constraint Programming.* ACM Symposium on Principles of Programming Languages, San Francisco,

References

Bobrow, D., Falkenhainer, B., Farquhar, A., Fikes, R., Forbus, K., et al. (1996). *A Compositional Modeling Language.* The Tenth International Workshop on Qualitative Reasoning, Fallenleaf Lake, CA, AAAI Press.

Iwasaki, Y., Fikes, R., Vescovi, M. and Chandrasekaran, B. (1993). *How Things are Intended to Work: Capturing Functional Knowledge in Device Design.* the 13th International Joint Conference on Artificial Intelligence, Chambery, France,

Low, C. M. and Iwasaki, Y. (1993). Device modelling environment: an interactive environment for modelling device behaviour. *Intelligent Systems Engineering* **1**(2): 115-145.